5-1998

Influence of Buffer Strip Width and Composition in Reduction of Agricultural Non-Point Source Contaminants

Tim Schmitt
University of Nebraska-Lincoln

INFLUENCE OF BUFFER STRIP WIDTH AND COMPOSITION IN REDUCTION OF AGRICULTURAL NON-POINT SOURCE CONTAMINANTS

by

Tim Schmitt

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Forestry, Fisheries & Wildlife

Under the Supervision of Professor Kyle D. Hoagland

Lincoln, Nebraska

May, 1998

INFLUENCE OF BUFFER STRIP WIDTH AND COMPOSITION IN REDUCTION OF AGRICULTURAL NON-POINT SOURCE CONTAMINANTS

Tim Schmitt, M.S.

University of Nebraska, 1998

Advisor: Kyle D. Hoagland

Vegetative buffer strips are a widely recommended best management practice (BMP) for reducing non-point source pollution, however information is needed about contaminant removal mechanisms and the impact that different design characteristics have on buffer performance to ensure that effective, land-efficient buffers are installed. The objectives of this study were to quantify the performance of vegetative buffers for a variety of common contaminants in surface runoff, to compare several vegetative compositions, and to examine the effects of doubling buffer width. A field study was performed on 40 field plots by simulating a storm event including rainfall and runoff. Input and outflow were measured for each plot and the difference provided information about the efficacy of each buffer design.

Doubling buffer width led to significantly greater reductions of runoff volume, sediment, several pesticides, and several forms of nitrogen and phosphorus. Reductions of sediment and associated contaminants were greater than soluble contaminants, but reductions of soluble contaminants were more greatly affected by doubling the width. Average reductions in concentrations of total dissolved phosphorus (TDP) increased from 24% by 7.5 m plots to 40% by 15.0 m plots, while total suspended solids (TSS) reductions increased from 77% (7.5 m) to 83% (15.0 m).

Comparisons between 2 yr-old buffers planted to grass only and those planted to grass, shrubs and trees showed no difference in the reduction of runoff volume or any of the measured contaminants. Generally, buffer vegetation performed better than an area of contour-planted grain sorghum, however the relative performance varied by contaminant type. Contaminant removal by contour-sorghum plots was actually greater or equal to buffer plots for the concentration of several soluble contaminants, including a 19% greater reduction of TDP, but buffer plots performed better for sediment and highly sorptive contaminants, including a 60% greater reduction of TSS than by contour-sorghum.

The use of vegetative buffers as a BMP in agricultural watersheds results in a range of benefits for the removal of specific contaminants, thus design of buffers depends on specific management goals.

Acknowledgments

I would like to thank the Nebraska Department of Environmental Quality for funding this project in cooperation with the Environmental Protection Agency - Region VII. I also want to thank the University of Nebraska's School of Agriculture and Natural Resources and the USDA Forest Service's National Agroforestry Center for the use of facilities and additional funding and support for this project.

I also want to acknowledge and thank all the people who helped me with this project. My advisor, Dr. Kyle Hoagland, who not only gave valuable advise, comments, help and education during this project, but also the support to be able to finish this thesis even while living in another state. The members of my committee: Dr. Tom Franti, who added valuable suggestions for the project and detailed comments which greatly improved this manuscript, and Dr. Linda Young, who repeatedly met with me to work out the statistical methods for this project, and in doing so taught me a lot about applied statistics. Dr. Mike Dosskey, who I worked closely with on this project from day-one, making the completion of such a large project possible and teaching me so much about scientific research over the past several years. Also, special thanks to the all the people who have helped me with the hours and hours of field and lab work, including my friends and colleagues who made the past several years fun, I wouldn't have been able to finish without your help. .... Thank you everyone for the education and friendships.

I also want to thank my wife for her love, support and encouragement which above anything else kept me going when things were frustrating or difficult.

Table of Contents

List of Tables

List of Figures

List of Appendices

INTRODUCTION

Non-point source (NPS) pollution has become a major concern in the United States because of poor surface water quality in some regions. In the Midwest, 60-80% of surface water pollution is caused by agricultural runoff (USEPA 1990). Because of this, vegetative buffer strips (VBS) have become a recommended best management practice (BMP) to help improve water quality, particularly for streams located in agricultural watersheds. This is most obvious in the USDA's recent (1997) National Conservation Buffer Initiative which sets a goal to install buffers along 2 million of the nation's 3.5 million riparian miles by 2002.

Recommendations on the use of VBS have been based on limited information, especially quantitative information on the ability of buffers to reduce the input of contaminants to aquatic ecosystems. As VBS become more widely promoted as a BMP for controlling NPS pollution, it becomes more important to know how effective different buffer designs are at reducing NPS pollutants. Design of effective and cost efficient buffers requires a greater understanding of the relationship between basic VBS characteristics such as width and vegetative composition and their ability to reduce various contaminants in runoff. This study was designed to examine how the width and type of riparian vegetation affect various types of contaminants in surface runoff leaving agricultural fields.

Contaminant Type

Contaminants in runoff are often categorized as sediment-bound, soluble, or some intermediate degree of sorptivity based on their relative ability to adsorb to sediment particles. The effectiveness of a buffer for reducing contaminants from runoff varies according to the mechanisms necessary to remove different contaminant types. Sediment and highly sorptive contaminants, such as phosphorus, are reduced in runoff by physical filtering and trapping of sediments by the vegetation, and by settling of sediment as runoff slows down or is ponded within a buffer. Numerous studies have shown that buffers are very effective sediment filters. Using grass buffer plots only 4.6 m wide, average sediment reductions of 66-72% have been shown, although the range for individual plots can vary more widely depending on variables such as slope, amount of rainfall, number of previous storms, etc. (Mickelson and Baker, 1993; Dillaha et al., 1989 and Magette et al., 1989).

Soluble contaminants, such as nitrates, are removed by infiltration of runoff into the soil; infiltration is greater in a buffer because of a greater root structure of the buffer vegetation and because soils tend to be less compacted than in the up-slope field. Soluble contaminants can also be affected by other mechanisms as runoff passes through a buffer. Dilution can reduce the concentration of contaminants as rainfall mixes with the runoff. Contaminants may also be removed by adsorption to soil particles and organic material while passing through the buffer. Misra et al. (1994) found that atrazine, metolachlor, and cyanazine were reduced by grass buffer strips at a greater rate than from infiltration alone, and attributed this difference to adsorption onto soil and dead/living vegetation. Previous literature has reported lower removal rates and much greater variability with buffers for pollutants other than sediment and highly sorptive contaminants such as total phosphorus (TP); several studies have even reported an increase of soluble contaminants from some buffers (Daniels and Gilliam, 1996; Osborne and Kovacic, 1993; Dillaha et. al., 1989 and Magette et. al., 1989). Most contaminants have intermediate properties of both solubility and sorptivity, so that the efficiency of buffer mechanisms for removing these pollutants represents some combination of these processes. A greater understanding of these processes and how they are affected by characteristics of vegetative buffers such as vegetative composition and width is needed to improve our ability to design effective, cost-efficient buffers and to be able to quantify the overall effectiveness of these buffers.

Buffer Width

The optimal width of a buffer for water quality benefits can vary widely depending on the type of contaminant. Factors such as slope, rainfall, size and management of the contributing runoff area, and sediment particle size will also influence a buffer's optimal width. Generally, a wider buffer will provide increased removal of contaminants from runoff, but the increase in removal will vary depending on the contaminant. Studies have shown that the width of a buffer is less important for sediment and associated contaminants because most sediment is removed in the first few meters at the top of the buffer (Robinson et al., 1996; Mickelson and Baker, 1993; Dillaha et al., 1989 and Doyle et al., 1977). These studies suggest that for sediment-related contaminants there are diminishing returns for longer buffers because a doubling in contaminant reduction will not result from a buffer which is twice as wide. Consistent results for the removal of soluble contaminants and pesticides is limited. An increased buffer width tends to provide significantly greater removal for soluble nutrients such as dissolved phosphorus (Dillaha et al., 1989 and Magette et al., 1989) and for certain pesticides (atrazine, metolachlor, and cyanazine) (Arora et al., 1993 and Mickelson and Baker, 1993), but a wide range of results have been found, including increases in soluble pollutants from some buffers. Bingham et al. (1980) found sediment and nutrient concentrations approached control levels in runoff from a buffer with a waste area to buffer area ratio of 1:1. Thus, further information is still needed about how buffer width affects removal rates for a variety of runoff contaminants, especially over a broad range of solubility and sorptivity.

Vegetative Composition

Vegetative composition is a basic physical characteristic for buffer strips that may affect how well contaminants are removed from surface runoff. Many studies have indicated that forested riparian vegetation provides excellent removal of soluble nutrients from shallow groundwater. Jordan et al. (1993), Jacobs and Gilliam (1985) and Peterjohn and Correll (1984) found nitrate removals of 90% or greater in sub-surface flow through forested buffers. Removal by forested buffers is thought to be mainly caused by the wetland hydrology of the riparian areas in these studies (Hill, 1996). In many Midwestern watersheds, contaminants are primarily transported as surface runoff, and studies have not looked at the effectiveness of forested buffers or buffers planted to trees for reducing contaminants in surface runoff.

The use of grass buffer strips to control contaminants in surface runoff has been widely studied. Single species of grass such as fescue, brome or orchardgrass (Magette et al., 1989; Dillaha et al., 1989 and Misra et al., 1994) or mixtures of grasses (Robinson et al., 1996; Arora et al., 1993; Mickelson and Baker, 1993 and Bingham et al., 1980) have been shown to be effective at removing sediment, sediment-bound contaminants, and some pesticides.

Very few studies have directly compared different vegetation types for their effectiveness at removing various contaminants from surface runoff. In many agricultural watersheds farmers cultivate immediately adjacent to the stream or drainage ditch leaving no established riparian vegetation. Planting these unvegetated riparian areas may be an effective way to improve water quality in agricultural watersheds. Direct comparisons of vegetation types are important to find the most effective taxa to plant for improving water quality. Doyle and Wolf (1977) compared 30-m wide forested buffers to 4-m wide grass (Fescue) buffers and concluded that the forested buffers were effective at reducing the concentration of total soluble N, P and K from dairy manure runoff in a distance of 3.8 m, and the grass buffers were also effective at reducing the loading rates of soluble NO_3-N, P, Na, and K in a distance of 4 m. Daniels and Gilliam (1996) examined the ability of grass and grass/forested buffers to reduce sediment and nutrients from runoff in areas with steeper slopes and less infiltration. Both designs were found to provide significant reductions in loading of sediment and nutrients, but the runoff must enter the buffer as sheet and rill flow for the buffers to be effective, particularly for forested buffers, were impeding ground cover is typically loose leaf material which can easily be washed away during larger runoff events.

Although previous studies have shown that different types of buffer vegetation can provide significant reductions of many contaminants, none have compared VBS to the alternative of leaving the land in an agricultural crop. Making this comparison is important to be able to quantify the performance of a VBS, because even an area of bare ground or agricultural crop has some capacity to absorb runoff and contaminants. Young et al. (1980) found that crop buffers of corn, orchardgrass, sorghum-sudangrass, and oats planted down-slope from a feedlot all provided significant reductions in runoff, sediment and several forms of nutrients. Mickelson, S. (pers. comm.) compared grass buffers to areas of bare ground and found that while grass buffers removed significantly more sediment and herbicides, bare ground did provide removal rates roughly half that of grass buffers, including 32% removal of sediment loading and 42% of atrazine.

Objectives

The objectives for this study were to (i) quantify relative removal rates by buffers for runoff volume, sediment, and several forms of nutrients and pesticides commonly found in agricultural runoff, (ii) compare the effectiveness of several vegetative compositions for reducing these contaminants in surface runoff and (iii) examine the effect that doubling buffer width has on removal of different types of contaminants.

MATERIALS AND METHODS

Field Plots

The study was conducted at the University of Nebraska's Agricultural Research and Development Center near Ithaca, Nebraska, USA (N41°09'00" - W96°30'00"). The area consists of Loess hills with fine soils, 69 cm of rainfall annually, primarily as spring thunderstorms, and is highly erodible during surface runoff because the area is primarily cropland. Soil at the site is a Sharpsburg silty clay loam with a gradient that runs from silty clay loam (31% clay) to sandy loam (10% clay) across the 400-m length of the study area.

Forty plots consisting of four different vegetative compositions were established. Each vegetative composition was planted in both 3 X 7.5 m and 3 X 15 m plots to simulate 7.5 m and 15 m wide buffer strips. Thus, the experimental design was a randomized complete block with a 4 X 2 factorial (vegetative composition X width), with each block of 8 plots replicated 5 times. Plots were constructed beginning in late April 1995 and the vegetation was planted by mid-June.

The first vegetative composition consisted of mixed grasses and forbs [termed "grass (2 yr)"]. Switchgrass seed (*Panicum virgatum* L. var. Blackwell) was broadcast in mid-June and again in the fall of 1995. Tall fescue (*Festuca arundinacea* Schreb. var. K-31) was broadcast the following spring, while other grasses and forbs, such as wild buckwheat (*Polygonum convolvulus* L.), foxtail (*Setaria* spp.) and alfalfa (*Medicago sativa* L.), immigrated from the surrounding hay field. By the second growing season, cover on these plots ranged from 70% to nearly 100%.

The second vegetative composition consisted of mixed grasses and forbs, under the same conditions as the first composition, as well as trees and shrubs [termed "grass/shrub/tree (2 yr)"]. The top half of plots consisted of the mixed grasses and forbs, while the lower half was planted to rows of shrubs [bush honeysuckle (*Lonicera sp.*) and golden currant (*Ribes odoratum* Wendl.)] and trees [eastern cottonwood (*Populus deltoides* Marsh.) and silver maple (*Acer saccharinum* L.)]. The 3 X 15 m plots consisted of 2 rows of shrubs (3/row) planted adjacent to the grass and 2 rows of trees (2/row) planted on the lower end of the plot, while the 3 X 7.5 m plots were planted with one row of trees and one row of shrubs (Figure 1). By the second growing season, trees were 1 - 2 m tall, shrubs were 0.5 - 1 m tall, and herbaceous cover (mowed to reduce competition with trees and shrubs) was 60 to 95% due to immigrating vegetation.

The third vegetative composition consisted of a mixture of various warm and cool season grasses with some forbs in a previously established (ca. 1970) hay field, which is harvested 2 or 3 times annually [termed "grass (25+ yr)"]. Dominant vegetation included switchgrass (*P. virgatum* L.), smooth brome (*Bromus inermis* Lyess.), indiangrass (*Sorghastrum nutans* L.), big bluestem (*Andropogon gerardii* Vitman), and little bluestem (*A. scoparius* Michx.); cover was nearly 100%. These plots were included to provide information about the performance of mature buffer strips as a comparison with our newly-established VBS.

The final vegetative composition consisted of contour-planted (standard 76 cm row spacing) grain sorghum (*Sorghum bicolor* (L.) Moench var. NC+ Hybrid® 6B50) with manual cultivation of weeds (hoeing) and no fertilizer or pesticides [termed "contour-sorghum"]. These plots were tilled and replanted each spring to provide an experimental control by mimicking cropland conditions with no vegetative buffer strip.

Buffer plots were constructed in a hay field down-slope (ca. 7% slope) from a crop field rotated between grain sorghum (*S. bicolor*) and soybeans (*Glycine max* (L.) Merr). Plot areas were delineated in the field, vegetation was killed by applying Round-up® to all but the grass (25+ yr) plots, and after two weeks the plots were plowed and tilled to represent converted crop ground. The plots were oriented and graded on the hillslope to achieve sheet flow. Prior to planting, soil samples were taken from each plot and analyzed for particle-size distribution as well as background contaminant levels (Appendices 1, 2 & 3). Results of the particle distribution tests indicated that two blocks were located on predominately silty clay loam soil, two on silt loam, and one on sandy loam. The plots were then planted to the various vegetative compositions; grass was broadcast then raked in, trees and shrubs were hand planted, and grain-sorghum was planted using a garden row-planter. Following planting, galvanized metal flashing was installed (25.4 cm-tall, 10 cm-deep) around the sides and bottom of each plot to contain flow within the plot during field trials and direct outflow at the bottom of the plot into an outflow spout (soil was packed tightly around the flashing to prevent water from running under it). PVC pipe (10.2 cm-diameter) was attached to the outflow spout and angled downhill to drain into a cattle tank for collecting all outflow coming from the bottom of the plot (Figure 1).

Experimental Trials

An experimental trial was performed on each plot to mimic a storm event with rainfall and agricultural runoff under typical field conditions. This was done by applying simulated rain and runoff from a modeled storm event to each plot and collecting the outflow at the down-slope end. The difference between the amount of simulated runoff applied to a plot and that collected in outflow represent the buffer strip performance of the plot.

Simulated Rainfall and Runoff Conditions

The modeled storm event was designed to mimic a typical spring thunderstorm with a one year return period for the field plot area (2.54 cm in 30 min) (Hershfield, 1961). Simulated rainfall was applied to plots at 5.08 cm/hr for 30 min using an overhead sprinkler system specifically designed for this experiment. The sprinkler consisted of a portable frame constructed from 1.91 cm PVC pipe, a 30 psi pressure regulator, and 7 Weathermatic® model 404SF "jet irrigator" sprinkler nozzles (each providing 2.7 L/min at 30 psi) spaced over a 5 m length to provide uniform coverage of a 3 X 7.5 m plot (2 sprinklers were used on 3 X 15 m plots).

The volume of simulated runoff (1890 L) used in the modeled storm was calculated using the Natural Resources Conservation Service Curve Number Method (U.S. Soil Conservation Service, 1972) for the following up-slope cropland conditions: contoured row crop (corn or milo), crop/fallow rotation, Sharpsburg silty-clay loam soil (hydrologic soil group B), wet antecedent soil moisture condition (type III; > 5.33 cm of rainfall in the prior 5 d), and an above-buffer field length of 81.2 m (by 3 m wide), which was chosen as a maximum length in which runoff typically does not gully in the study area (Gilley, J., pers. comm.) (this length would represent approximately 10.8:1 and 5.4:1 field-to-buffer area ratios for the 7.5 m and 15 m plots, respectively).

Agricultural chemicals and sediment added to the simulated runoff represent typical peak concentrations of contaminants that could be found in corn field runoff during a spring storm event in eastern Nebraska (Table 1). Concentrations were estimated from the literature.

Potassium bromide was also added to the runoff mixture as a conservative tracer so that a distinction could be made between runoff and rainfall water that constituted the outflow at the bottom of each plot. This is important to: (i) show the fate of water and contaminants within the buffer, and (ii) correct the concentration and load of contaminants in the outflow for amounts that may have been applied to plots from well water used for the simulated rainfall, because naturally occurring rainfall would typically have very low or no pollutant contamination.

Simulated runoff was prepared immediately prior to a field trial by adding 1890 L of water to a 3780 L polyethylene tank (Snyder Industries; Lincoln, Nebraska). Water for the runoff mixture and for simulated rainfall came from a well at the research site. Pre-measured amounts of the six contaminants and the potassium bromide tracer were added to the tank and stirred with a circulating pump system for one hour until the mixture was homogeneous. Simulated runoff was applied to the up-slope portion of a plot by pumping the mixture through a PVC manifold at a rate of 75.7 L/min. The manifold was constructed from a 3 m-long section of 2.54 cm-diameter PVC pipe with holes placed every 10 cm to spread the water uniformly across the top of the plot as sheet flow. During the application of runoff, circulation was maintained in the tank to keep sediments suspended.

Field Trials

Field trials were conducted from July 4-14, 1996 during the second growing season of the buffer vegetation. Trails were designed to mimic the progression of rainfall and runoff on VBS during a typical spring storm (Figure 2). The modeled type III antecedent soil moisture condition was produced by pre-wetting a plot with 19 mm of simulated rainfall at four different times in the five days preceding the trial (total of 76 mm). Pre-wetting also ensured uniform soil moisture between plots. No natural rainfall occurred immediately prior to or during the trials.

Field trials were performed by first applying simulated rainfall at a rate of 5.08 cm/hr to a plot. After 10 minutes of rainfall, simulated runoff from the mixing tank was applied at a rate of 75.7 L/min to the up-slope end of the plot. Rainfall continued on the plot for another 20 minutes until 2.54 cm of rain had been applied, and runoff was applied for 35 minutes until the 1890 L runoff mixture was emptied from the tank.

Water that reached the down-slope end of the plot was collected in a cattle tank and homogenized, using a circulation pump and mixing manifold, as grab samples were collected for analysis of the various contaminants. Volume of outflow was then measured using a flow meter as the solution was pumped out of the cattle tank. In addition to the outflow samples, one random sample per block of plots was collected from the simulated runoff mixture immediately prior to it's application on the up-slope end of a plot. One random sample per block of plots was also collected from the water used for simulated rainfall. Samples for sediment and nutrient analyses were collected in acid-washed LDPE bottles, and samples for pesticide analyses were collected in acid-washed 1 L amber-glass bottles. All samples were immediately stored on ice while in the field.

Laboratory Procedures

Field samples were analyzed for soluble and sediment-bound forms of atrazine, alachlor, and permethrin, and for total suspended solids (TSS), total nitrogen (TN), nitrate+nitrite nitrogen (N+N), total phosphorus (TP), bioavailable phosphorus (BAP), total dissolved phosphorus (TDP), and bromide.

At the end of each day of field trials, the sample bottles were returned to the lab. Samples for analysis of pesticides and TSS were stored in a cooler at 4°C. Samples for analysis of sediment-associated nutrients were stored at -10°C. Soluble nutrient samples (including the bromide tracer) were centrifuged at 3,500 X g for 7 min, filtered through a 0.45 μm Gelman GN Metricel® membrane filter, and the filtrate stored at -10°C. Samples were stored as described until all trials were completed (7 d).

Bromide concentration was determined at the University of Nebraska Soil Testing Lab on filtered samples using ion chromatography with a Dionex DX 100 chromatograph (USGS 1985). Pesticide levels were determined for both sediment and soluble forms by Olson Biochemistry Laboratories at South Dakota State University. Pesticide samples were prepared by filtration through 0.45 μm nylon filters. Pesticides were extracted from the filtrate with methylene chloride (U.S. EPA 1980) and from the sediment with ethyl acetate (Sanchez-Brunete et. al. 1994, Gorder and Dahm 1981) by sonicating in warm solvent after standing overnight. Concentrations of the pesticide extracts were determined by gas chromatography on a Varian 3700 and Tremetrics/Finningan 9001 using nitrogen-phosphorus detection for atrazine and alachlor and electron capture detection for permethrin. TSS was determined by the difference in mass of a Gelman type A/E® glass-fiber filter and the mass of the filter with oven-dried sediment (method 2540D, APHA 1992). The entire contents of each 125-ml sample bottle was used for TSS analysis to eliminate sub-sampling error. N+N was determined on filtered samples using the hydrazine reduction method (Downes 1978); BAP was determined on unfiltered samples using the method described by Sharpley (1993); TDP and TP were determined using persulfate digestion (Menzel and Cowin 1965) on filtered and unfiltered samples, respectively, and measured by colorimetry (Murphy and Riley, 1962); TN was determined on unfiltered samples via persulfate digestion (D'Elia et al. 1977), and measured by UV- spectrophotometry corrected for organic matter (APHA 1992). Colorimetric and UV tests for forms of N and P were performed using a Perkin-Elmer lambda 3B® UV-VIS spectrophotometer.

High amounts of sediment interfered with TN and TP analyses by creating high variability among sub-samples and causing unstable spectrophotometer readings. Variability and error from sub-sampling was minimized by pipetting sub-samples from field bottles as they mixed vigorously on a magnetic stirplate. Samples with sediment also caused unstable spectrophotometer readings due to sedimentation in the detection chamber. This problem was eliminated by adding an additional step to the analysis method. After digestion and colorization steps were performed, each sample was drawn into an acid-washed Becton-Dickinson® 20-cc plastic syringe. A Gelman Acrodisc® 25mm glass fiber syringe filter was subsequently attached to the syringe, several mL of sample were ejected to flush the filter, and then sample was injected into a spectrophotometer cuvette for reading.

Data Analysis

In order to calculate reduction of runoff and contaminants and perform statistical analyses of the data, concentration and loading values for each contaminant were first corrected for minor contaminant additions from irrigation water used in the simulated rainfall. Corrections were made using the bromide tracer results and a two-component mixing model. First, the contributions of "rain" and "runoff" to the outflow collected at the down-slope end of a plot were calculated using two mass balance equations:

$$V_o = V_r + V_t \quad (1)$$

$$C_o V_o = C_r V_r + C_t V_t \quad (2)$$

These equations were then reduced to:

$$V_r = V_o - V_t \quad (3)$$

$$V_t = [(C_o - C_r) / (C_t - C_r)] * V_o \quad (4)$$

where V is volume, C is the concentration of the bromide tracer and the subscripts o, r and t indicate the outflow at the down-slope end of an individual plot, the simulated rainfall component and the tank runoff mixture component, respectively (Sklash, 1990). Next, a corrected concentration value for a given contaminant could be calculated for outflow from each plot using:

$$CC_o = [(V_o * C_o) - (V_r * \overline{C}_r)] / V_o \quad (5)$$

where CC_o is the corrected outflow concentration and $\overline{C}_r$ represents the average concentration of a given contaminant in all simulated rainfall samples.

Corrected concentrations and loadings of the nine contaminants, as well as runoff volume, were each analyzed by ANOVA for a randomized complete block design using SAS® (version 6.12; SAS Institute, Inc., Cary, NC), with treatments in a 4 X 2 factorial arrangement (vegetative composition X width). Contrasts were chosen for the specific objectives of this research, but were not all orthogonal. To control the experiment-wise error-rate, significance of a contrast was evaluated only if the corresponding overall F-test was significant. A 5% significance level was chosen as an arbitrary level for all tests.

Three treatments had missing concentration data from one or more replications caused by a lack of runoff at the down-slope end of the plots [grass (2 yr), 15.0 m: plot 2-4; grass (25+ yr), 15.0 m: plots 1-8, 2-5, and 3-3 and; contour-sorghum, 15.0 m: plots 2-6, 3-1, and 5-8]; volume and loading from these plots were entered as 0 for statistical analyses. Significant ($P < 0.05$) vegetative composition X width interactions were analyzed for simple effects.

Percent reductions as reported in the text and shown in figures 3 & 4 were calculated using:

$$\% \text{ reduction} = [(\overline{C}_t - C_o) / \overline{C}_t] * 100 \qquad (6)$$

where $\overline{C}_t$ represents the average concentration (or load) of a given contaminant in all tank runoff mixture samples, and C_o is the concentration (or load) of a given contaminant in outflow collected at the down-slope end of an individual plot.

Calculations for percent differences in reductions between contour-sorghum and buffer vegetative compositions as reported in the text and in figure 5 were made using:

$$\% \text{ difference} = [(\overline{C}_{o\text{-}cs} - C_o) / \overline{C}_{o\text{-}cs}] * 100 \qquad (7)$$

where $\overline{C}_{o\text{-}cs}$ is the average concentration (or load) for a given contaminant found in outflow collected at the down-slope end of the contour-sorghum plots, with one average calculated for 7.5 m plots and one for 15.0 m plots and each used accordingly; C_o is the concentration (or load) of a given contaminant in the runoff collected at the down-slope end of an individual buffer plot.

RESULTS

Width

The overall trend was a substantially greater reduction of volume and contaminants in surface runoff by the 15.0 m plots than by the 7.5 m plots. The volume of runoff leaving the bottom of buffer plots was significantly greater ($P = 0.0012$) from 7.5 m plots (46% average reduction for all vegetative compositions) than from 15.0 m plots (70% reduction) (Table 2; Figure 4). Because loads are computed as volume multiplied by concentration of a contaminant, volume greatly contributed to the reduction of contaminant loading. Thus, load reductions of the nine contaminants were also significantly greater by the 15.0 m plots (ranging from a 75% reduction for atrazine to 95% for TSS) than by the 7.5 m plots (from 52% for atrazine to 87% for TSS) (Figure 4).

Reductions in contaminant concentrations were also significantly affected by increasing buffer width (Table 2). TN was significantly reduced by doubling buffer width ($P = 0.0001$), from an average reduction by all vegetative compositions of 29% on 7.5 m plots to a 42% reduction on 15.0 m plots. N+N showed a similar effect to changing width ($P = 0.0009$), from an average reduction of 23% by 7.5 m plots to 38% by 15.0 m plots. TSS was also significantly affected by width ($P = 0.0004$), with 7.5 m plots reducing TSS by an average of 77% [ranging from 63% by contour-sorghum plots to 89% by grass (25+ yr) plots], and 15.0 m plots providing an 83% reduction [ranging from 65% to 93%]. Doubling buffer width led to significantly greater concentration reductions for all measured forms of phosphorus (Table 2; Figure 3). Permethrin reductions were significantly different from doubling width ($P = 0.0187$), as 7.5 m plots only showed a

36% reduction in concentration, while 15.0 m plots provided a 66% reduction. Reduction of alachlor concentration was significant ($P = 0.0429$) and increased from 22% by 7.5 m plots to 35% by 15.0 m plots. Atrazine displayed a vegetative composition X width interaction ($P = 0.0099$), thus simple effects were examined (Table 3). Atrazine concentration reductions by grass (25+ yr) plots were significantly greater ($P = 0.0340$) in 15.0 m plots (43% reduction) than in 7.5 m plots (18%); however, there was no significant difference caused by width for atrazine in either grass (2 yr) or grass/shrub/tree (2 yr) plots.

Vegetative Composition

Overall, vegetative composition did not significantly affect runoff volume ($P = 0.0786$), N+N concentration ($P = 0.1599$) or N+N loading ($P = 0.1575$), consequently significance of differences in the reduction of runoff volume and N+N by individual vegetative compositions could not be determined. Nevertheless, vegetative composition did significantly affect both concentration and loading of the remaining contaminants (Table 2).

There were no significant differences between the grass (2 yr) plots and grass/shrub/tree (2 yr) plots for the reduction of TN, alachlor, permethrin, TDP, BAP, TP, and TSS concentrations (Table2). Vegetative composition X width interactions were significant for atrazine concentrations ($P = 0.0099$), thus simple effects were examined (Table 3). There was no significant difference in atrazine reductions between grass (2 yr) and grass/shrub/tree (2 yr) plots at a width of 15.0 m ($P = 0.1654$), while differences between 7.5 m plots were nearly significant ($P = 0.0525$). The results for load removal were similar, as there were no significant differences between the grass (2 yr) and grass/shrub/tree (2 yr) plots in loading reductions of any contaminants (Table 2).

Generally, when comparing the reduction of contaminants by grass (2 yr), grass/shrub/tree (2 yr) and grass (25+ yr) plots with that by contour-sorghum plots, the buffer vegetation provided greater reductions in the concentration of contaminants than did the contour-sorghum (Figure 5). Comparisons between grass (2 yr) plots and contour-sorghum plots resulted in no significantly different reductions for the concentration of alachlor, permethrin or BAP, but there were significant differences for concentrations of TN, TDP, TP and TSS (Table 2). Grass (2 yr) plots of both widths provided average reductions greater than contour-sorghum plots of 8% for TN, 27% for TP, and 50% for TSS, but contour-sorghum plots provided a 28% greater reduction in TDP than the grass (2 yr) plots. Simple effects for atrazine concentration were significant ($P = 0.0017$) between the two plot types at 7.5 m, but not at 15.0 m ($P = 0.2100$); 7.5 m contour-sorghum plots provided a 37% greater reduction in atrazine than the grass (2 yr) plots. In comparison to reductions in concentration, loading reductions were significantly greater by contour-sorghum than by grass (2 yr) plots for atrazine (71% greater reduction), alachlor (61%) and TDP (95%) (Table 2; Figure 5).

Comparisons between grass/shrub/tree (2 yr) and contour-sorghum plots were not significantly different for the concentration of TN or alachlor, but they were significantly different for permethrin, BAP, TDP, TP and TSS concentrations (Table 2). Grass/shrub/tree (2 yr) plots of both widths provided an average reduction in the concentration of contaminants that was greater than contour-sorghum plots by 12% for

BAP, 30% for TP, 37% for permethrin, and 54% for TSS; contour-sorghum plots provided a 23% greater reduction in the concentration of TDP then the grass/shrub/tree (2 yr) plots. Atrazine concentrations were significantly different between the two plot types at 15.0 m, but not at 7.5 m; 15.0 m grass/shrub/tree (2 yr) provided a 20% greater reduction in atrazine than contour-sorghum plots. In comparison to reductions in concentration, loading reductions were significantly greater by grass/shrub/tree (2 yr) plots than contour-sorghum plots for TSS (28%), but contour-sorghum provided a 130.6% greater reduction in TDP loading (Table 2; Figure 5).

Comparisons between grass (25+ yr) and contour-sorghum plots resulted in significantly different reductions by plots for alachlor, permethrin, TN, BAP, TP and TSS concentrations, but not TDP (Table 2). Grass (25+ yr) plots of both widths provided an average reduction in concentration greater than contour-sorghum plots of 19% for TN, 30% for BAP, 33% for alachlor, 51% for TP, 69% for permethrin, and 75% for TSS. Simple effects were significant between the two plot types at 15.0 m, but not at 7.5 m for atrazine (Table 5); 15.0 m grass (25+ yr) plots provided a 43% greater reduction in the concentration of atrazine than contour-sorghum plots. In addition to greater reductions of contaminant concentrations, grass (25+ yr) provided significantly greater reductions than contour-sorghum plots for loads of permethrin (68% greater reductions), TP (56%) and TSS (79%) (Table 2; Figure 5).

DISCUSSION

Width

In general, doubling the width of the buffer plots significantly reduced runoff volume and both the concentration and loading of a wide range of contaminants typically found in runoff from agricultural watersheds. Runoff volume was reduced by an average of 46% by 7.5 m plots of all vegetative compositions, and 70% by 15.0 m plots. Although nearly all the contaminants were significantly reduced by a wider buffer, the relative reduction varied according to the type of contaminant. Sediment and contaminants that are highly sorptive showed much smaller reductions from doubling the width than did soluble contaminants and runoff volume. For example, atrazine reduction by grass (25+ yr) buffers increased from 18% in 7.5 m plots to 43% in 15.0 m plots, while reduction of TSS only went from 89% to 93% in 15.0 m plots. Thus, sediment and associated contaminants exhibited diminishing returns, as reductions of TSS by 7.5 m plots was already very high, such that the relatively minor additional reduction in a 15.0 m wide buffer may not justify the cost of removing twice the amount of land from production. These are decisions presently made by land managers according to their individual goals, but recent initiatives and cost-share programs may eventually lead to the implementation of more standardized criteria (USEPA 1990).

Vegetative Composition

Overall, there was no significant difference in the amount of runoff volume among the different vegetative compositions. This was somewhat surprising because during the trials it appeared that there were large differences in runoff from the plots.

There appeared to be much lower runoff volumes from grass (25+ yr) plots than from others; even contour-sorghum plots seemed to have lower runoff than grass (2 yr) or grass/shrub/tree (2 yr) plots. This discrepancy in the statistical analysis and what we saw in the field is probably caused by high variability between plots; reduction of runoff by individual 15.0 m plots ranged from 33% to 100%, and from 5% to 98% by 7.5 m plots. In addition, the moderate-sized storm event that was simulated in this study, combined with a year of below average precipitation, was not greatly sufficient to saturate all of the plots. Consequently, runoff was collected at the bottom of only 2 out of 5 replicates from 15.0 m plots of both contour-sorghum and grass (25+ yr), making them appear more effective at reducing runoff and loading and adding to the variability. This high variability combined with a limited number of replicates likely led to a lack of significant differences observed in the field. The data from this study suggests differences, but they are not conclusive regarding whether vegetative composition affects the volume of runoff leaving a field, and they are also limited to comparisons made for a single storm magnitude.

Multiplying the runoff volume by contaminant concentration to calculate loading of contaminants from each plot also increased variability of the two factors, thus greatly increasing the variability of load values. Consequently, fewer significant differences between the different vegetative compositions were found for contaminant loads than for contaminant concentrations. Because of this, loading values may not be the best means of comparing performance between the different vegetative compositions and widths, especially given the high levels of variability for runoff volume found in this study. On the other hand, the amount of contaminant loading that can be expected to leave fields with or without buffers is an important measure of the impact that vegetative buffers can have on the water quality of adjacent or nearby streams and lakes. This is an important consideration for regulatory agencies who use total daily maximum loads (TDML) for the management of water quality within watersheds, and results collected in this study provide practical data about the potential reduction of contaminant loads by vegetative buffers.

Generally, there was no difference in performance between grass (2 yr) and grass/shrub/tree (2 yr) plots. The reason that the two vegetative compositions performed so closely is probably because of the similarity of the vegetation and the relative maturity of the plots. Even by the second growing season, grass and weeds had immigrated into the bottom of the grass/shrub/tree (2 yr) plots so that there was very little bare ground around trees and shrubs and cover was similar to grass (2 yr) plots. Because the plots were only in the second year of growth when the experiment was conducted, the trees and shrubs were not yet well established, and any additional benefit they may provide was not yet apparent. In addition, runoff only occurred as surface flow, which is typical in many agricultural watersheds in the Midwest. Much of the previously recorded benefits attributed to trees has been for removal, primarily of nitrates, from subsurface flow such as that found in riparian wetland forests of the eastern coastal plain region (Hill, 1996). Thus, even mature trees and shrubs may not have provided added water quality benefits under the conditions of this study. Trimble (1997) suggested that grassed channels stored more sediment than forested reaches, and further suggested that forested stream banks, compared to grassed ones, can destabilize stream channels by promoting erosion. In addition, Daniels and Gilliam (1996) found that forested ephemeral channels have little under story vegetation and were ineffective at removing sediment during large storm events because of their low resistance to flow. Although Peterjohn and Correll (1984) reported significant decreases in nitrates, they also reported an average annual increase in discharge from a riparian forest for ammonium-N, organic-N, TP, and organic-C. These studies suggest that trees and shrubs alone may not provide added water quality benefit, and in fact could be detrimental if not properly designed and maintained. Future studies of these plots after vegetation has become more established should provide important information on differences in their potential to reduce NPS contaminants.

The buffer plots exhibited an interesting pattern of contaminant removal based on the sorptivity of the contaminant. The more highly sorptive the form of the contaminant was, the greater the reduction of the contaminant by the buffer plots (Figures 3 & 4). The reduction in phosphorus concentration by 7.5 m grass (25+ yr) plots increased from 29% for TDP (a soluble form of P) to 53% for BAP (a measure of both soluble and some sorptive P) to 71% for TP (the majority of which is highly sorptive), and additionally, increased to 89% for TSS. This pattern probably occurred because filtering and trapping of sediment (and bound contaminants) by vegetation found in the buffer plots is the most dominant mechanism of removal by vegetative buffers. Therefore, contaminants with the lowest adsorption to sediment (such as TDP) are least impacted by this removal mechanism and exhibit the lowest removal rates.

Even though high rates of contaminant removal by plots were found in this study and have been reported in previous research, this removal by vegetative buffers means very little if the same land planted in crops would also provide high contaminant removal rates. In this study, comparisons were made between the three buffer vegetative compositions and a contour-planted sorghum crop to demonstrate the relative performance of buffers as compared to leaving the land planted to a crop. Overall, the comparisons showed that buffer vegetation provided greater removal of contaminant concentrations than the contour-sorghum. The absolute performance of buffer vegetation, however, was diminished when compared with an area of contour-planted sorghum. Grass (2 yr) plots reduced the concentration of TSS by an average of 82% and TDP by 24%, but contour-sorghum also provided a 64% reduction of TSS and 40% of TDP. The relative performance of the buffer vegetation was also dependent on the type of contaminant. Reduction of contaminant concentration by contour-sorghum was actually greater or equal to the buffer vegetations for the least sorptive contaminants, including TDP and atrazine, but buffer vegetations provided greater rates of removal for sediment and highly sorptive contaminants, such as TP. Concentrations of the forms of P measured in this study followed this pattern (Figure 5). The concentration of TDP was more greatly reduced by contour-sorghum plots (-19%) than by the average of grass (2 yr), grass/shrub/tree (2 yr) and grass (25+ yr) plots. On the other hand, the three buffer vegetations provided much higher reductions (+36%) of TP than contour-sorghum. Reduction of BAP ranked between TP and TDP (+17%). This pattern probably occurred because the denser vegetation found in the buffer plots provides greater filtering and trapping of sediment than does contour-planted sorghum, but this fails to explain why the reduction in concentration of several soluble contaminants was greater by contour-sorghum plots.

Although variability of runoff volume was too high to show differences between vegetative compositions, runoff volume and the loading rates for many contaminants were much lower from contour-sorghum plots than from grass (2 yr) and grass/shrub/tree (2 yr), especially for 15.0 m plots (Figure 5). Because outflow runoff was collected from only 2 of the 5 replicates of 15.0 m contour-sorghum plots, the effectiveness of 15.0 m contour-sorghum plots to reduce contaminant loading may appear greater than it actually is. The relatively large reductions in runoff volume and contaminants by contour-sorghum plots was probably also caused in part by the size of the plots. Young et al. (1980) stated, "whenever narrow rectangular field plots [such as the ones in this study] are tilled and planted across slope, there is a risk of overestimating the effectiveness of the treatment in reducing soil and water losses ... as compared with treatment effects on large size fields." However, this factor would only account for a portion of the performance by contour-sorghum plots, especially the significant reductions in concentration found for many of the contaminants in this study.

When looking at the results of comparisons between buffer vegetative compositions and contour-sorghum, it is also important to keep in mind that field trials were performed at a single point in time each year under a condition with well formed contour rows and grain sorghum having matured for approximately a month and a half. This condition is somewhat idealized for a "buffer" area planted to a crop and would not be present year-round. In fact, many storm events would typically occur earlier in the season when crop vegetation provides less cover or is not present at all. On the other hand, reductions of sediment (32%), atrazine (42%), metolachlor (37%) and cyanazine (43%) have been observed even by bare ground (Mickelson, S., pers. comm.). This suggests that a potential buffer area, even without buffer vegetation, has some ability to absorb runoff and contaminants. Further, it suggests that while vegetative buffers do provide valuable water quality protection, their performance as previously reported in the literature may be overstated, so that it is important to compare vegetative buffers to an alternative land use such as crop vegetation.

Grass (25+ yr) plots were included, in part, as part of a long-term study to examine the change in newly planted buffers over time. Although we did not directly compare grass (25+ yr) and 2-year buffers here, there are some obvious trends in the data. Generally, there were greater contaminant reductions by grass (25+ yr) plots than by the grass (2 yr) and grass/shrub/tree (2 yr) plots. It was interesting to note that patterns (such as greater contaminant reductions with increased adsorptive properties) occurring for the different types of contaminants in the 2 yr buffers or between the 2 yr buffers and the contour-sorghum plots were similar for the grass (25+ yr) plots, but more pronounced. It was also interesting that under less than ideal planting and growing conditions (i.e. two subsequent years with below average precipitation) buffer vegetation still matured quickly, with a significant increase in vegetation observed from the first growing season into the second and third seasons. These (25+ yr) plots provided information about what can be expected of the performance of newly planted buffers after they become established, and how performance may change over time. This is important because many agricultural areas in the Midwest do not have well established buffers and a variety of recent initiatives now provide assistance for their installation.

Interactions

Significant vegetative composition by width interactions were found for atrazine, but are probably not indicative of a buffer's ability to reduce atrazine from runoff. Only two measurements for atrazine concentration were collected from 15.0 m contour-sorghum plots and from 15.0 m grass (25+ yr) plots. One of the measurements from contour-sorghum (plot 4-2) was high, indeed higher than the average concentration of runoff added to the plots. This may be because of high background contamination of atrazine within this particular plot, as atrazine levels in soil samples collected prior to planting were nearly four times higher than the average level found in the other contour-sorghum plots. The plots are located downslope from a field where atrazine is used regularly, and plot 4-2 may receive drainage from that field. Recalculating the ANOVA for atrazine without the atrazine value from plot 4-2 indicated that the vegetative composition by width interaction for atrazine was not significant ($P = 0.1525$).

Buffer Mechanisms

As surface runoff passes through a buffer, contaminants are reduced by several physical and chemical mechanisms; infiltration, dilution, filtering and settling, and transformations. The type of contaminant determines which mechanisms are responsible for a reduction, while the physical characteristics of the buffer strip (such as vegetative composition and width) determine the magnitude of contaminant reduction. Infiltration was a dominant mechanism in this study, as volume was reduced by an average of 58%.

Dilution via contaminants mixing with rainfall while passing through a buffer also causes a reduction in the concentration of contaminants leaving a buffer. Because bromide is a conservative tracer, its concentration reduction indicated how much dilution took place. Bromide concentration was reduced 16% by 7.5 m plots and nearly doubled (28%) by 15.0 m plots, implying that dilution for a given storm event is dependent upon the width of a buffer. Concentration reductions of contaminants which are greater than that of bromide indicate that mechanisms other than dilution are acting. These mechanisms include filtering and settling of sediment-bound contaminants, or transformations within the buffer of contaminants in solution (i.e. binding to the surface of soil and organic material, direct uptake by plants, or microbial processes). Physical filtering and settling within the buffer was also a prominent mechanism, as TSS loads were reduced on average 91%, and the concentration of TSS leaving the plots was 80% lower than the input. Average concentration reductions of TDP (26%) were similar to those of bromide (22%) from grass (2 yr) and grass/shrub/tree (2 yr) plots, but TDP reductions were about 50% greater than bromide reductions on grass (25+ yr) plots, and about 100% greater on contour-sorghum plots. This indicates that some type of transformation acting on TDP was present on grass (25+ yr) and contour-sorghum plots, but not on 2-yr old plots.

A relatively broad foundation of literature has been accumulated that can be used to calculate and predict to some degree how much infiltration of runoff, filtration of sediment and dilution by rainfall will occur within a buffer. Other transformations of contaminants within buffers have been reported by this study and several others, but little is known about what specific transformations are occurring, and even less is known about what characteristics of buffers may influence these transformations. Research should be continued to establish the types and rates of these transformations occurring within a buffer and to determine if buffers can be designed to improve removal of contaminants by these transformations.

Studies have shown that pesticides such as atrazine and alachlor can have a significant impact on algal communities and primary productivity of aquatic ecosystems (Spawn et al., 1997; Hoagland et al., 1993). In addition, most aquatic systems in the Midwest are P-limited and relatively large inputs of soluble phosphorus from agricultural runoff have caused accelerated eutrophication to occur in these systems. Because many soluble pollutants can have such a detrimental impact on aquatic systems, it is important to know how characteristics of vegetative buffers affect the removal of soluble contaminants. Little data has been available regarding the contribution to contaminant removal by specific mechanisms occurring within a buffer, especially for soluble contaminants such as TDP and atrazine. However, this study provides needed information that separates the effects of the various removal mechanisms acting upon runoff within vegetative buffers. The study showed that while infiltration and physical filtering or settling of sediment were the most significant removal mechanisms, other mechanisms including dilution and some form(s) of contaminant transformation did act upon contaminants to a lesser degree within the buffers.

References

APHA (American Public Health Association). 1992. Standard Methods for the Examination of Water and Waste Water. 18th edition. American Public Health Association, New York, New York, USA.

Arora, K., J.L. Baker, S.K. Mickelson, and D.P. Tierney. 1993. Evaluating herbicide removal by buffer strips under natural rainfall. ASAE Paper No. 932593, ASAE, St. Joseph, MI.

Bingham, S.C., P.W. Westerman, and M.R. Overcash. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. Trans. ASAE 23: 330-336.

Comfort, S.D., P.J. Shea, and F.W. Roeth. 1994. Understanding pesticides and water quality in Nebraska. Nebraska Cooperative Extension EC 94-135.

Daniels, R.B., and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60:246-251.

D'Elia, C.F., P.A. Steudler, and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnol. Oceanogr. 22:760-764.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Trans. ASAE 32:513-519.

Downes, M.T. 1978. An improved hydrazine reduction method for the automated determination of low nitrate levels in freshwater. Wat. Res. 12:673-75.

Doyle, R.C., G.C. Stanton and D.C. Wolf. 1977. Effectiveness of forest and grass buffer strips in improving the water quality of manure polluted runoff. ASAE Paper No. 77-2501, ASAE, St. Joseph, MI.

Gorder, G.W., and P.A. Dahm. 1981. Analysis of carbofuran and atrazine in soil samples. J. Agric. Food Chem. 29:629-634.

Hershfield, D.M. 1961. Rainfall frequency atlas of the U.S. U.S. Weather Bureau, Tech Paper 40. May 1961.

Hill, A.R. 1996. Nitrate removal in stream riparian zones. J. Environ. Qual. 25:743-755.

Hoagland, K.D., R.W. Drenner, J.D. Smith, and D.R. Cross. 1993. Freshwater community responses of agricultural pesticides: effects of atrazine and bifenthrin. Environ. Toxicol. Chem. 12:627-637.

Jacobs, T.C., and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. J. Environ. Qual. 14:472-478.

Jordan, T.E., D.L. Correll, and D.E. Weller. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. J. Environ. Qual. 22:467-473.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Trans. ASAE 32: 663-667.

Menzel D.W., and N. Corwin. 1965. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. Limnol. Oceanogr. 10:280-282.

Mickelson, S.K., and J.L. Baker. 1993. Buffer strips for controlling herbicide runoff loses. ASAE Paper No. 932084, ASAE, St. Joseph, MI.

Misra, A.K., J.L. Baker, S.K. Mickelson, and H. Shang. 1994. Effectiveness of vegetative buffer strips in reducing herbicide transport with surface runoff under simulated rainfall. ASAE Paper No. 942146, ASAE, St. Joseph, MI.

Murphy, J., and J. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

Osborne, L.L, and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwat. Biol. 29:243-258.

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475.

Robinson, C.A., M.Ghaffarzadeh, and R.M. Cruse. 1996. Vegetative filter strip effects on sediment concentration in cropland runoff. J. Soil and Water Cons. 50:227-230.

Sanshez-Brunete, C., L. Martinez, and J.L.Tadeo. 1994. Determination of corn herbicides by GC-MS and GC-NPD in environmental samples. J. Agric. Food Chem. 42:2210-2214.

Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron-impregnated paper. J. Environ. Qual. 22:597-601.

Sklash, M.G. 1990. Environmental isotope studies of storm and snow melt runoff generation. In: (Anderson, M.G. and Burt, T.P., eds.), Process Studies in Hillslope Hydrology. John Wiley & Sons, NY. pp. 401-435.

Spawn, R.L., K.D. Hoagland, and B.D. Siegfried. 1997. Effects on alachlor on an algal community from a midwestern agricultural stream. Environ. Toxicol. Chem. 16:785-793.

Trimble, S.W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25: 467-469.

U.S. Environmental Protection Agency. 1990. National water quality inventory, 1988. Report to Congress, Office of Water, EPA 440-4-90-003.

U.S. Environmental Protection Agency. 1980. Manual of Analytical Methods for the Analysis of Pesticides in Humans and Environmental Samples. U.S. Environmental Protection Agency, Health Effects Research Laboratory, Research Triangle Park, NC 27711, EPA-600/8-80-038, June, 1980, Section 10.

U. S. Geological Survey. 1985. Anions, ion-exchange, chromatographic, automated. In Fishman, M.J. and L. Friedman (eds.), Methods for Determination of Inorganic Substances in Water and Fluvial Sediments. Open-File Report 84-495. U.S. Dept. of Interior, pp. 170-171.

U.S. Soil Conservation Service. 1972. SCS National Engineering Handbook. Section 4. Hydrology. U.S. Department of Agriculture, Washington, D.C.

Young, R.A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. J. Environ. Qual. 9: 483-487.

TABLES

Table 1. Form and concentration, including nominal and measured concentrations, of the various contaminants added to simulated runoff mixture.

CONTAMINANTS	NOMINAL	MEASURED†
sediment (mg/L)	10,000	10,019
Total-Nitrogen (mg/L):	59	67.8
in well water	6	7.0
on sediment	3	‡
NH_4NO_3 33-0-0 fertilizer	50	‡
Total Phosphorus (μg/L):	1,100	4,428
in well water	300	247
on sediment	200	‡
superphosphate 0-46-0 fertilizer§	600	‡
atrazine (Aatrex®) (μg/L)	500	436
alachlor (Confidence®) (μg/L)	250	221
permethrin (Ambush®) (μg/L)	20	6.0
potassium bromide tracer (mg/L)	10	9.4

† Measured concentration is an average of five tank samples (one per block).
‡ Not measured.
§ Beads ground to powder.

Table 2. P-values† for comparisons of contaminant concentration and loading found in outflow from buffer plots.

COMPARISON	VOL	N+N	TN	ATR	ALA	PER	TDP	BAP	TP	TSS
	CONTAMINANT CONCENTRATION									
Model (F-test)		**0.0272**	**0.0008**	**0.0061**	**0.0030**	**0.0135**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Vegetative Composition		0.1599	**0.0069**	**0.0036**	**0.0006**	**0.0287**	**0.0013**	**0.0001**	**0.0001**	**0.0001**
Grass (2 yr) vs Contour-sorghum		0.1435	**0.0454**	0.3162	0.6444	0.1094	**0.0015**	0.1053	**0.0001**	**0.0001**
Grass/Shrub/ Tree (2 yr) vs Contour-sorghum		0.0814	0.0824	0.2935	0.1374	**0.0389**	**0.0071**	**0.0160**	**0.0001**	**0.0001**
Grass (25+ yr) vs Contour-sorghum		**0.0316**	**0.0007**	**0.0106**	**0.0008**	**0.0037**	0.9902	**0.0001**	**0.0001**	**0.0001**
Grass (2 yr) vs Grass/Shrub/Tree (2 yr)		0.7453	0.7257	**0.0230**	0.2950	0.5680	0.4126	0.3106	0.4580	0.4738
Width (7.5 m vs 15.0 m)		**0.0009**	**0.0001**	0.3510	**0.0429**	**0.0187**	**0.0001**	**0.0001**	**0.0001**	**0.0004**
Vegetative Composition X Width		0.4789	0.3492	**0.0099**	0.0588	0.7036	0.8524	0.4841	0.0862	0.2556
	CONTAMINANT LOADING									
Model (F-test)	**0.0086**	**0.0016**	**0.0008**	**0.0019**	**0.0012**	**0.0011**	**0.0003**	**0.0003**	**0.0001**	**0.0001**
Vegetative Composition	0.0786	0.1575	**0.0498**	**0.0113**	**0.0092**	**0.0225**	**0.0122**	**0.0229**	**0.0114**	**0.0012**
Grass (2 yr) vs Contour-sorghum	0.1719	0.3907	0.3447	**0.0181**	**0.0430**	0.7215	**0.0259**	0.2327	0.8355	0.1356
Grass/Shrub/ Tree (2 yr) vs Contour-sorghum	0.1099	0.3950	0.1613	0.1135	0.1883	0.2621	**0.0204**	0.2955	0.9497	**0.0433**
Grass (25+ yr) vs Contour-sorghum	0.4951	0.2503	0.1993	0.4594	0.1902	**0.0049**	0.7763	0.0932	**0.0069**	**0.0001**
Grass (2 yr) vs Grass/Shrub/Tree (2 yr)	0.8050	0.9937	0.6367	0.3872	0.4470	0.5756	0.9159	0.8788	0.7866	0.5668
Width (7.5 m vs 15.0 m)	**0.0012**	**0.0001**	**0.0001**	**0.0003**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Vegetative Composition X Width	0.4098	0.4802	0.4250	0.3823	0.6107	0.0779	0.4639	0.3681	0.2923	0.1228

† Bold values are significant at the 5% level.

Table 3. Summary of P-values† for the simple effects for atrazine concentrations of each vegetative composition‡ and selected vegetative comparisons at 7.5 and 15.0 m widths.

	ATRAZINE				
PARAMETER	7.5-15.0	G2-CS	GST-CS	G25-CS	G2-GST
Vegetative composition					
Grass (2 yr)	0.1239				
Grass/shrub/tree (2 yr)	0.2416				
Grass (25+ yr)	**0.0340**				
Contour-sorghum	**0.0137**				
Width					
7.5 m		**0.0017**	0.1408	0.4942	0.0525
15.0 m		0.2100	**0.0230**	**0.0013**	0.1654

† Bold values are significant at the 5% level.
‡ G2 = grass (2 yr); GST = grass/shrub/tree (2 yr); G25 = grass (25+ yr); CS = contour-sorghum

FIGURES

Figure 1. Schematic of a 3 X 7.5 m grass/shrub/tree (2 yr) plot showing the position of the vegetation, runoff application system at the top of the plot, and the outflow collection system on the downslope end.

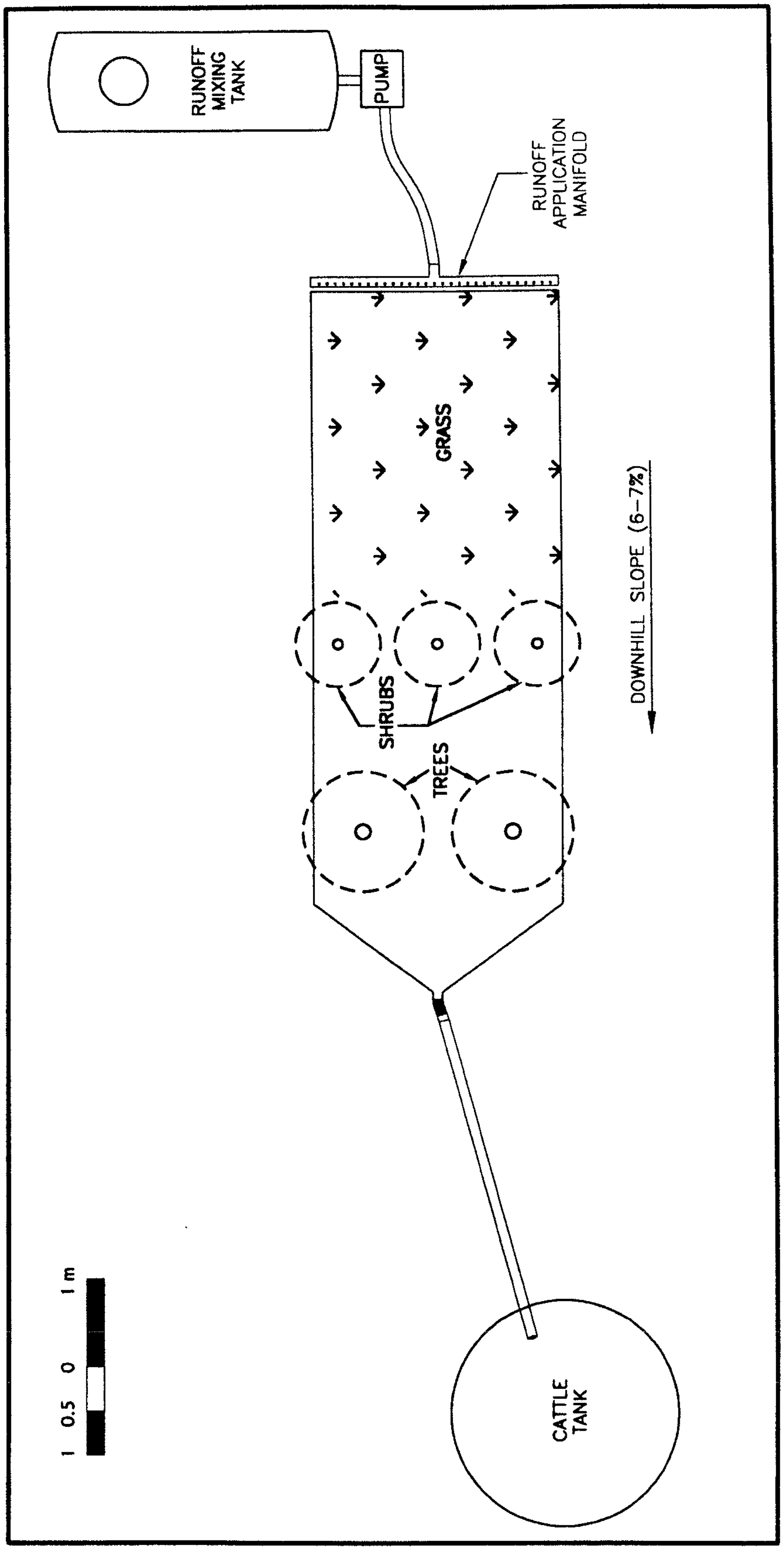

RUNOFF
MIXING
TANK
PUMP
RUNOFF
APPLICATION
MANIFOLD
GRASS
DOWNHILL SLOPE (6–7%)
SHRUBS
TREES
CATTLE
TANK
1 0.5 0 1 m

Figure 2. Scheduled sequence and timing of tasks during a field trial.

Day 1

Pre-wet plot with 19 mm of rain

Day 3

Pre-wet plot with 19 mm of rain

Day 4

Pre-wet plot with 19 mm of rain (a.m.)

Pre-wet plot with 19 mm of rain (p.m.)

Day 5 - Field Trial:

Trial Process	Time
Add runoff ingredients to tank and mix	-50:00
Begin application of rainfall to plot	0:00
Apply runoff to top of plot	10:00
Stop rainfall on plot	30:00
Stop runoff on plot	~35:00
Outflow from bottom of plot stops	~40:00

Figure 3. Percent reduction of contaminant concentration by 7.5 m and 15.0 m buffer plots of each vegetative composition. Contaminants are listed from least adsorptive to most adsorptive along the X-axis within each grouping. The position of nitrogen and phosphorus forms within groupings is based on the method of analysis; pesticides are arranged according to their organic carbon partition coefficient (K_{oc}) (Comfort et al. 1994). N+N and TN = nitrate-nitrite and total nitrogen, respectively; ATR = atrazine; ALA = alachlor; PER = permethrin, TDP, BAP and TP = total dissolved, bioavailable and total phosphorus, respectively; TSS = total suspended solids

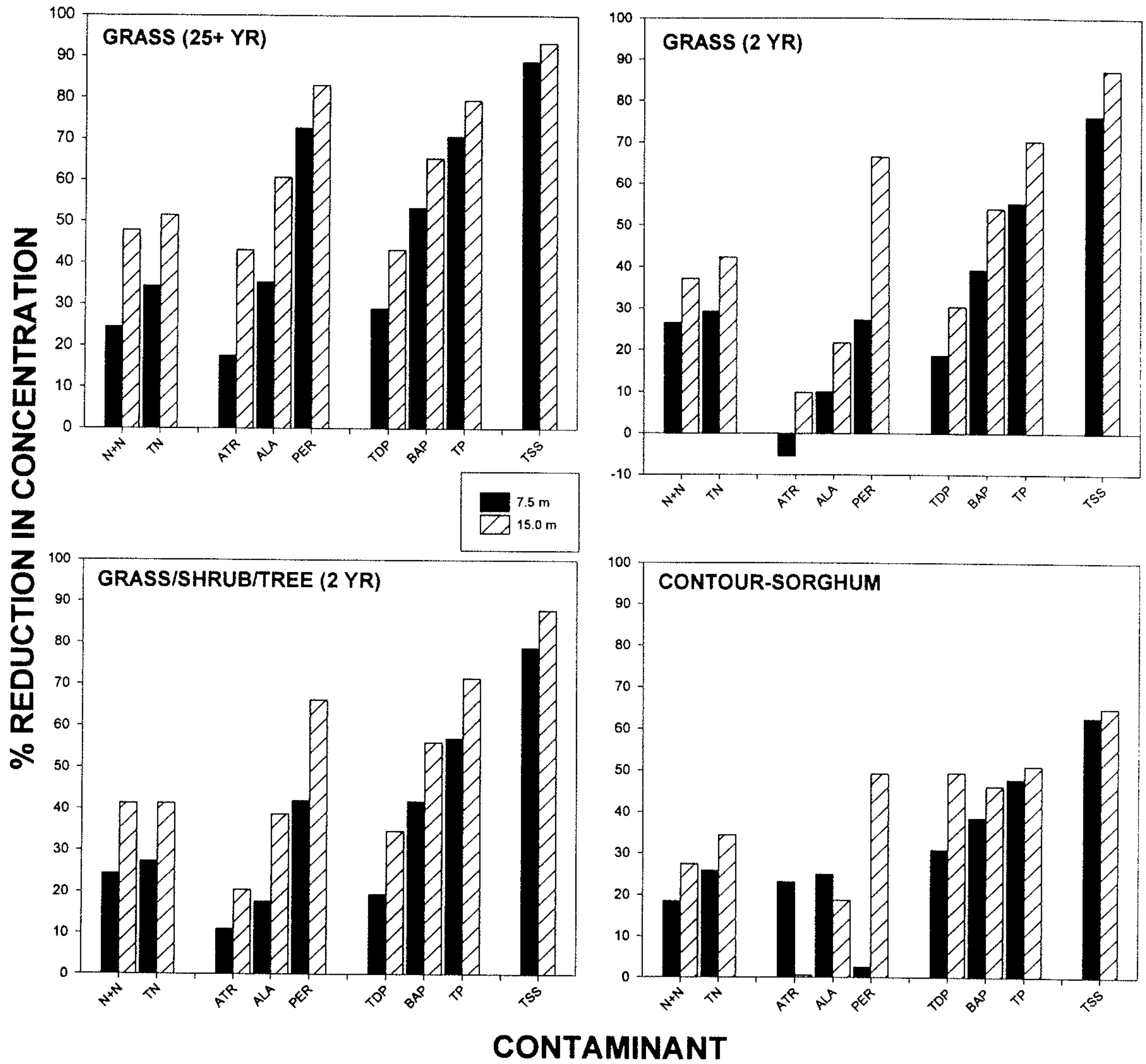

GRASS (25+ YR)
GRASS (2 YR)
GRASS/SHRUB/TREE (2 YR)
CONTOUR-SORGHUM
7.5 m
15.0 m
% REDUCTION IN CONCENTRATION
CONTAMINANT
N+N
TN
ATR
ALA
PER
TDP
BAP
TP
TSS

Figure 4. Percent reduction in contaminant loading and runoff volume by 7.5 m and 15.0 m buffer plots of each vegetative composition. Contaminants are listed from least adsorptive to most adsorptive along the X-axis within each grouping, where runoff volume and TSS represent the extremes at each end of the axis. The position of nitrogen and phosphorus forms within groupings is based on the method of analysis; pesticides are arranged according to their organic carbon partition coefficient (K_{oc}) (Comfort et al. 1994). N+N and TN = nitrate-nitrite, and total nitrogen, respectively; ATR = atrazine; ALA = alachlor; PER = permethrin, TDP, BAP and TP = total dissolved, bioavailable and total phosphorus, respectively; TSS = total suspended solids

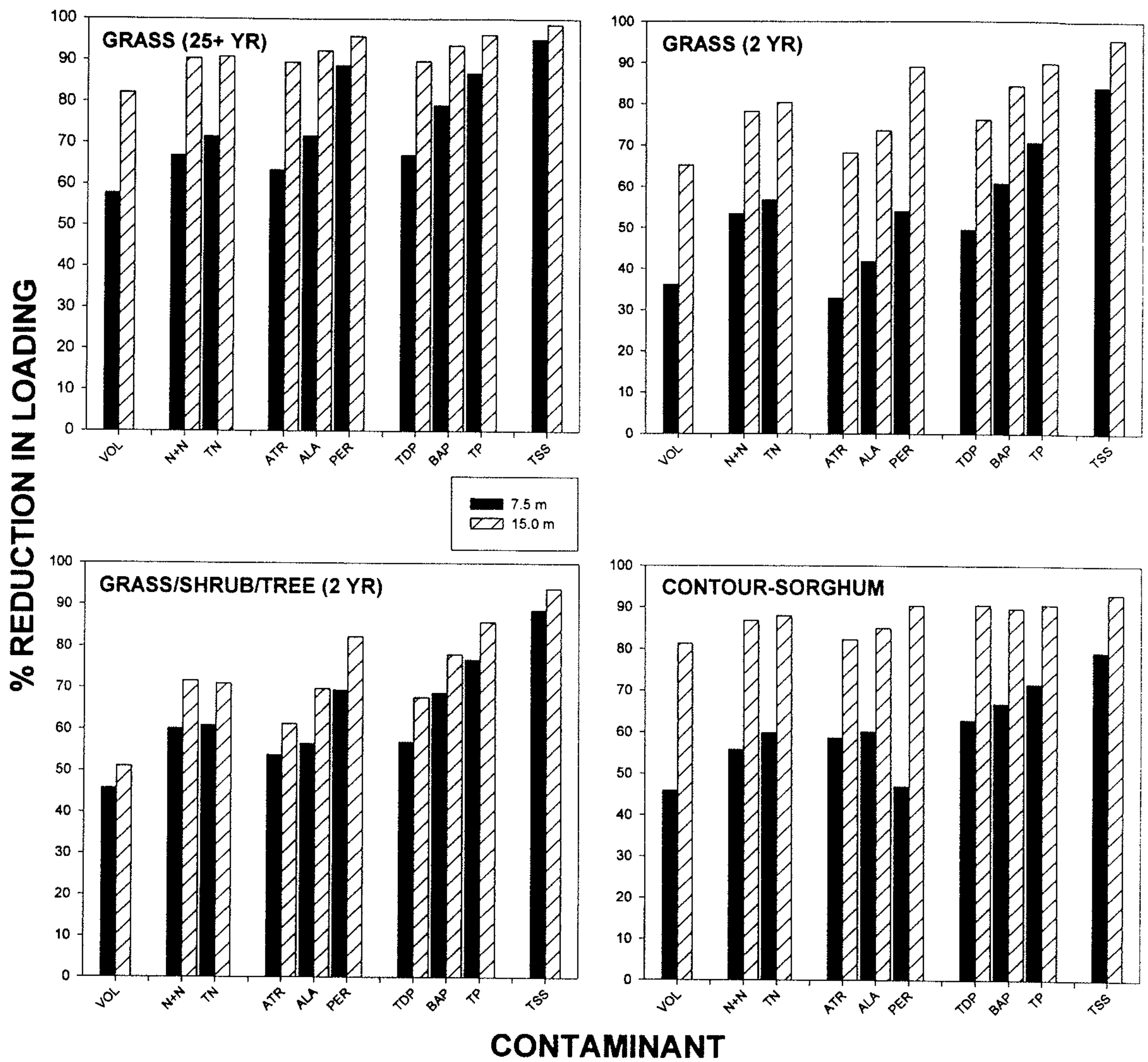
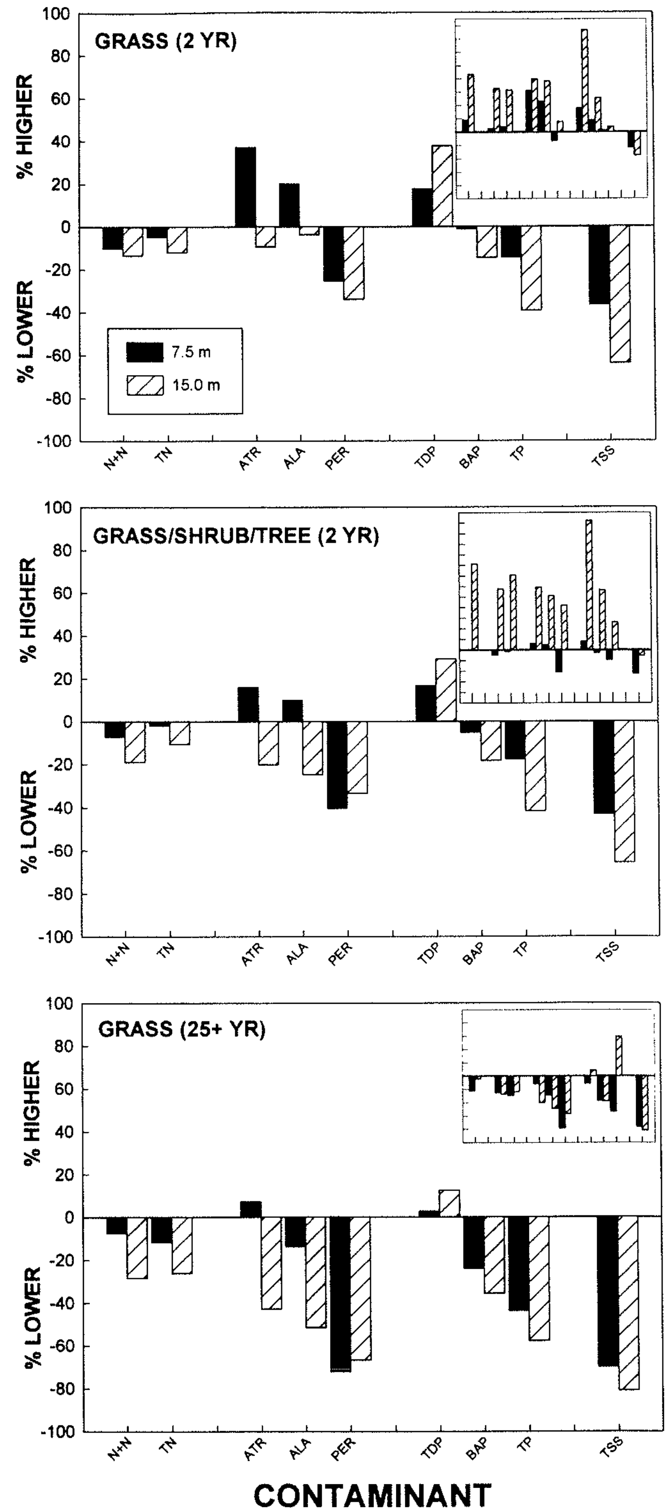

GRASS (25+ YR)
GRASS (2 YR)
GRASS/SHRUB/TREE (2 YR)
CONTOUR-SORGHUM
7.5 m
15.0 m
% REDUCTION IN LOADING
CONTAMINANT
VOL
N+N
TN
ATR
ALA
PER
TDP
BAP
TP
TSS
0
10
20
30
40
50
60
70
80
90
100

Figure 5. Difference in the concentration (large graphs) and load (inserts) of contaminants leaving the three buffer vegetative compositions compared to contour-sorghum plots for both 7.5 m and 15.0 m widths. Difference is expressed as percent higher or lower than the levels leaving contour-sorghum plots. Axis labels are the same for both large and insert graphs, except the first set of bars on insert graphs represents runoff volume. Contaminants are listed from least adsorptive to most adsorptive along the X-axis within each grouping, where runoff volume and TSS represent the extremes at each end of the axis. The position of nitrogen and phosphorus forms within groupings is based on the method of analysis; pesticides are arranged according to their organic carbon partition coefficient (K_{oc}) (Comfort et al. 1994). N+N and TN = nitrate-nitrite and total nitrogen, respectively; ATR = atrazine; ALA = alachlor; PER = permethrin, TDP, BAP and TP = total dissolved, bioavailable and total phosphorus, respectively; TSS = total suspended solids


GRASS (2 YR)
GRASS/SHRUB/TREE (2 YR)
GRASS (25+ YR)
% HIGHER
% LOWER
7.5 m
15.0 m
100
80
60
40
20
0
-20
-40
-60
-80
-100
N+N
TN
ATR
ALA
PER
TDP
BAP
TP
TSS
CONTAMINANT

APPENDICES

Appendix 1. Analytical methods for soil samples. Soil samples from each plot, and sediment used in the runoff mixture, were collected by compositing three cores taken to a depth of 15 cm. Samples were air dried for 7 days.

PARAMETER	PROCEDURE	REFERENCE
Total P	energy dispersive x-ray fluorescence (EDXRF)	Knudsen et al. 1981
Extractable-P	mild-acid extraction and colorimetry	Bray and Kurtz 1945
Total N	dry combustion - LECO	Wong and Kemp 1977
Nitrate-N	KCl extraction and colorimetry	Keeny and Nelson 1982
Ammonium	KCl extraction and colorimetry	Keeny and Nelson 1982
Atrazine	super critical fluid extraction - GC/MS	USEPA 1980
Desisopropyl (atrazine metabolite)	super critical fluid extraction - GC/MS	USEPA 1980
Desethyl (atrazine metabolite)	super critical fluid extraction - GC/MS	USEPA 1980
Alachlor	super critical fluid extraction - GC/MS	USEPA 1980

Appendix 2. Soil particle-size analysis for each plot and for sediment used in the runoff mixture. Particle-size was measured on a composite sample of three cores taken from a plot to a depth of 15 cm.

Block	Plot	Plot type†	% sand	% coarse silt	% fine silt	% very fine silt	% clay	Textural class
1	1	G2 - 7.5 m	67.52	7.11	9.15	2.03	14.19	SANDY LOAM
1	2	CS - 15.0 m	69.09	6.60	10.15	0.51	13.66	SANDY LOAM
1	3	GST - 7.5 m	63.46	9.15	11.18	1.52	14.69	SANDY LOAM
1	4	G25 - 7.5 m	46.80	16.38	17.92	3.58	15.32	LOAM
1	5	GST - 15.0m	53.63	15.30	13.77	0.51	16.79	SANDY LOAM
1	6	G2 - 15.0 m	59.29	12.23	11.72	0.51	16.26	SANDY LOAM
1	7	CS - 7.5 m	39.49	19.50	19.50	11.29	10.22	SILT LOAM
1	8	G25 - 15.0 m	32.13	22.64	23.66	7.20	14.36	SILT LOAM
2	1	GST - 15.0m	23.44	24.85	22.77	2.07	26.87	LOAM
2	2	CS - 7.5 m	20.61	25.79	26.82	2.06	24.72	SILT LOAM
2	3	G25 - 7.5 m	21.51	27.38	33.07	6.72	11.33	SILT LOAM
2	4	G2 - 15.0 m	21.96	26.37	22.75	3.62	25.30	SILT LOAM
2	5	G25 - 15.0 m	20.02	26.84	26.33	7.23	19.58	SILT LOAM
2	6	CS - 15.0 m	22.16	27.85	20.11	3.09	26.78	SILT LOAM
2	7	G2 - 7.5 m	22.48	25.85	22.75	3.62	25.30	SILT LOAM
2	8	GST - 7.5 m	17.06	28.01	28.01	14.52	12.41	SILT LOAM
3	1	CS - 15.0 m	14.56	30.90	28.84	10.30	15.41	SILT LOAM
3	2	G2 - 7.5 m	17.75	29.83	25.72	9.26	17.45	SILT LOAM
3	3	G25 - 15.0 m	18.38	30.30	24.65	3.08	23.58	SILT LOAM
3	4	CS - 7.5 m	20.38	28.27	34.95	9.76	6.64	SILT LOAM
3	5	G2 - 15.0 m	13.18	27.40	27.71	9.00	22.71	SILT LOAM
3	6	GST - 15.0m	15.47	27.85	22.69	7.22	26.77	SILT LOAM
3	7	GST - 7.5 m	13.79	30.47	24.79	6.20	24.75	SILT LOAM
3	8	G25 - 7.5 m	15.15	28.99	25.36	4.14	26.36	SILT LOAM
4	1	G2 - 15.0 m	12.83	31.01	26.36	4.65	25.14	SILT LOAM
4	2	CS - 15.0 m	14.86	27.93	25.86	4.14	27.22	SILTY CLAY LOAM
4	3	G25 - 7.5 m	12.49	24.91	27.50	4.15	30.95	SILTY CLAY LOAM
4	4	G25 - 15.0 m	13.73	25.88	30.54	4.66	25.18	SILT LOAM
4	5	GST - 7.5 m	12.66	26.93	29.00	5.18	26.23	SILT LOAM
4	6	G2 - 7.5 m	9.49	26.95	28.50	4.66	30.39	SILTY CLAY LOAM
4	7	GST - 15.0m	12.64	31.08	24.86	4.14	27.27	SILTY CLAY LOAM
4	8	CS - 7.5 m	16.73	27.99	24.88	2.07	28.32	SILTY CLAY LOAM
5	1	G2 - 7.5 m	17.12	22.84	24.40	4.15	31.48	SILTY CLAY LOAM
5	2	GST - 7.5 m	21.04	23.79	24.83	4.66	25.68	SILT LOAM
5	3	CS - 7.5 m	23.24	25.82	21.69	4.13	25.12	SILT LOAM
5	4	G25 - 15.0 m	18.69	28.03	23.88	3.11	26.29	SILT LOAM
5	5	G2 - 15.0 m	14.54	30.11	23.88	3.63	27.84	SILTY CLAY LOAM
5	6	GST - 15.0m	15.57	26.99	23.88	3.11	30.44	SILTY CLAY LOAM
5	7	G25 - 7.5 m	14.73	26.93	24.86	2.07	31.41	SILTY CLAY LOAM
5	8	CS - 15.0 m	13.98	27.01	27.53	5.19	26.30	SILT LOAM
sediment used in runoff			11.90	24.70	28.82	4.12	30.46	SILTY CLAY LOAM

† G2 = grass (2 yr); GST = grass/shrub/tree (2 yr); G25 = grass (25+ yr); CS = contour-sorghum

Appendix 3. Background levels of nutrients and pesticides, including two metabolites of atrazine, found in each plot and sediment used in the runoff mixture . Contaminants were measured on a composite sample of three cores taken from a plot to a depth of 15 cm.

Block	Plot	Plot type†	P mg/L	TKN % N	NH_4 mg/L	NO_3 mg/L	bromide mg/L	desisopropyl (atrazine) μg/L	desethyl (atrazine) μg/L	atrazine μg/L	alachlor μg/L
1	1	G2 - 7.5 m	6.8	0.105	11.00	12.50	0.182	1.8	0.9	3.7	0.0
1	2	CS - 15.0 m	6.5	0.100	13.30	11.70	0.000	0.7	0.4	2.9	0.0
1	3	GST - 7.5 m	6.3	0.122	12.70	14.70	0.204	0.7	0.4	2.8	0.0
1	4	G25 - 7.5 m	3.4	0.167	6.58	5.09	0.163	0.6	0.4	1.8	0.0
1	5	GST - 15.0m	5.0	0.142	14.80	14.90	0.163	0.7	0.7	5.2	2.4
1	6	G2 - 15.0 m	4.3	0.103	9.90	16.40	0.467	0.7	0.6	3.4	0.7
1	7	CS - 7.5 m	5.4	0.172	14.10	18.70	0.000	1.1	0.6	4.4	2.0
1	8	G25 - 15.0 m	3.4	0.217	6.65	4.89	0.000	0.7	0.7	4.4	0.0
2	1	GST - 15.0m	4.6	0.187	8.30	7.71	0.000	1.0	1.9	4.9	2.3
2	2	CS - 7.5 m	6.9	0.224	12.00	10.30	0.182	0.9	1.3	7.4	1.5
2	3	G25 - 7.5 m	3.7	0.253	7.15	5.23	1.210	1.4	1.6	0.0	0.0
2	4	G2 - 15.0 m	5.0	0.209	9.24	9.92	0.000	0.7	1.1	4.5	0.0
2	5	G25 - 15.0 m	4.4	0.268	5.62	6.80	0.328	1.1	0.8	0.0	0.0
2	6	CS - 15.0 m	5.4	0.198	10.60	10.70	0.000	0.8	1.2	2.3	2.6
2	7	G2 - 7.5 m	6.3	0.252	8.63	13.20	0.156	0.9	1.7	3.9	0.0
2	8	GST - 7.5 m	6.6	0.252	9.70	14.20	0.000	1.4	1.1	2.9	0.0
3	1	CS - 15.0 m	6.4	0.224	9.69	15.90	0.052	1.2	2.5	9.9	4.1
3	2	G2 - 7.5 m	7.8	0.235	13.40	19.30	0.505	1.0	1.4	11.7	4.9
3	3	G25 - 15.0 m	3.8	0.226	5.12	4.54	0.258	1.0	1.7	3.9	0.0
3	4	CS - 7.5 m	7.1	0.200	10.20	21.20	0.486	1.2	2.8	8.7	3.4
3	5	G2 - 15.0 m	12.2	0.211	13.10	16.70	0.175	1.4	3.4	9.7	3.3
3	6	GST - 15.0m	5.5	0.201	10.10	10.30	0.000	0.9	3.2	6.6	0.0
3	7	GST - 7.5 m	6.8	0.211	7.52	18.90	0.000	1.0	2.8	4.7	0.0
3	8	G25 - 7.5 m	4.6	0.210	4.10	5.09	0.000	0.9	3.9	3.8	0.0
4	1	G2 - 15.0 m	7.0	0.250	11.70	21.00	0.000	1.5	0.7	10.6	0.0
4	2	CS - 15.0 m	7.1	0.217	9.47	21.70	0.000	1.5	2.1	15.4	0.0
4	3	G25 - 7.5 m	4.6	0.265	5.84	5.74	0.125	1.0	1.2	3.7	0.0
4	4	G25 - 15.0 m	3.7	0.218	4.83	5.23	0.695	0.7	0.7	0.0	0.6
4	5	GST - 7.5 m	6.7	0.237	9.50	16.40	0.000	1.1	1.4	7.0	2.5
4	6	G2 - 7.5 m	8.3	0.235	11.10	14.50	0.000	1.2	1.5	0.0	0.0
4	7	GST - 15.0m	5.1	0.213	8.99	17.60	0.000	1.4	0.7	0.0	0.0
4	8	CS - 7.5 m	5.9	0.198	9.70	14.20	0.071	0.8	0.9	0.0	0.0
5	1	G2 - 7.5 m	5.3	0.235	10.70	10.80	0.099	0.9	1.3	6.5	5.5
5	2	GST - 7.5 m	5.4	0.213	9.99	16.90	0.000	0.7	1.1	6.3	0.0
5	3	CS - 7.5 m	5.1	0.199	10.60	14.90	0.334	0.7	0.7	0.0	0.0
5	4	G25 - 15.0 m	3.7	0.242	6.01	4.58	0.128	0.5	1.1	4.0	0.2
5	5	G2 - 15.0 m	6.9	0.238	11.40	13.50	0.000	0.8	1.4	5.2	0.0
5	6	GST - 15.0m	7.4	0.246	11.70	22.60	0.000	0.5	0.7	5.3	0.0
5	7	G25 - 7.5 m	3.8	0.233	5.49	3.53	0.023	0.5	1.4	0.0	0.0
5	8	CS - 15.0 m	7.4	0.256	8.90	27.10	0.000	0.8	0.9	0.0	0.0
sediment used in runoff			98.0	0.200	3.83			1.6	1.0	6.0	10.2

† G2 = grass (2 yr); GST = grass/shrub/tree (2 yr); G25 = grass (25+ yr); CS = contour-sorghum

Appendix 4. Raw data collected† from trials conducted during the second growing season of newly planted buffer vegetation (July 4-14 1996). Data for each plot is the concentration of contaminant found in samples collected at the downslope end of a plot.

block	plot	plot type‡	Volume (L)	Bromide (mg/L)	TSS (mg/L)	TN (mg/L)	NN (mg/L)	TP (ug/L)	BAP (ug/L)	TDP (ug/L)	Atrazine (ug/L)	Alachlor (ug/L)	Permethrin (ug/L)
1	7	CS - 7.5 m	1260.4	7.88	5446.26	55.48	26.99	2654.58	1026.63	374.05	322.90	144.83	3.38
2	2	CS - 7.5 m	766.0	8.05	3336.99	53.51	25.91	2332.81	1188.72	448.46	341.11	178.54	5.41
3	4	CS - 7.5 m	1135.8	8.04	3293.84	48.13	20.18	2192.04	1116.68	478.63	267.62	137.59	10.84
4	8	CS - 7.5 m	1026.4	8.22	3636.99	44.09	24.67	2413.25	1098.67	420.31	396.44	156.55	4.33
5	3	CS - 7.5 m	924.5	8.49	3052.74	54.96	20.04	2151.82	1152.70	478.63	347.42	212.05	5.43
1	2	CS - 15.0 m	1196.2	7.40	4013.99	43.57	19.89	2373.03	1062.65	341.88	374.90	172.25	3.13
2	6	CS - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3	1	CS - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	2	CS - 15.0 m	566.0	7.43	3028.77	48.33	22.95	2071.38	936.57	355.96	491.51	187.42	3.00
5	8	CS - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1	4	G25 - 7.5 m	45.3	6.67	930.56	41.09	19.39	1065.85	720.44	345.90	257.23	103.00	1.58
2	3	G25 - 7.5 m	694.3	7.33	1204.11	46.68	22.45	1307.18	846.52	436.40	427.32	183.00	1.93
3	8	G25 - 7.5 m	977.4	7.79	1295.21	45.44	21.12	1508.28	936.57	494.72	401.40	165.96	2.16
4	3	G25 - 7.5 m	1188.7	8.05	1113.01	43.88	19.69	1407.73	900.55	518.85	346.56	128.88	1.12
5	7	G25 - 7.5 m	1079.2	8.42	1130.56	51.54	27.88	1468.06	936.57	520.86	363.65	134.62	1.46
1	8	G25 - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	5	G25 - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3	3	G25 - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	4	G25 - 15.0 m	467.9	6.55	588.28	31.26	15.05	925.08	630.38	408.24	228.49	70.33	0.18
5	4	G25 - 15.0 m	1218.9	6.37	778.08	38.92	17.32	1065.85	738.45	412.26	268.01	104.13	1.87
1	1	G2 - 7.5 m	1792.5	8.02	3389.44	32.71	18.55	2393.14	1188.72	402.21	442.81	221.90	3.93
2	7	G2 - 7.5 m	717.0	8.37	2237.93	54.85	19.69	1950.71	1134.69	540.97	453.73	194.90	4.90
3	2	G2 - 7.5 m	1147.2	8.26	2020.55	53.72	22.11	1830.05	1062.65	536.95	576.32	261.29	4.67
4	6	G2 - 7.5 m	1234.0	8.34	2247.26	52.99	24.23	2091.49	1080.66	532.93	382.56	148.69	6.85
5	1	G2 - 7.5 m	1139.6	8.04	2023.29	49.99	21.66	1809.94	1044.64	536.95	442.03	169.05	1.58
1	6	G2 - 15.0 m	1234.0	6.28	1283.80	35.91	21.02	1266.96	810.49	452.49	383.86	151.51	2.03
2	4	G2 - 15.0 m	0.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3	5	G2 - 15.0 m	1226.4	6.39	1299.32	42.43	17.37	1387.62	864.53	488.68	427.42	167.81	1.43
4	1	G2 - 15.0 m	358.5	6.90	1238.36	40.68	20.18	1387.62	900.55	500.75	429.23	158.57	1.42
5	5	G2 - 15.0 m	467.9	6.78	1307.59	46.16	18.01	1528.39	954.58	486.67	330.50	215.24	3.23

block	plot	plot type‡	Volume (L)	Bromide (mg/L)	TSS (mg/L)	TN (mg/L)	NN (mg/L)	TP (ug/L)	BAP (ug/L)	TDP (ug/L)	Atrazine (ug/L)	Alachlor (ug/L)	Permethrin (ug/L)
1	3	GST - 7.5 m	1279.2	7.73	2159.31	45.54	23.93	1830.05	1008.61	440.42	329.92	155.53	0.67
2	8	GST - 7.5 m	471.7	8.34	2366.67	52.99	26.89	2071.38	1170.71	563.09	471.49	213.85	4.35
3	7	GST - 7.5 m	1041.5	7.54	2058.50	52.47	19.59	1950.71	1116.68	547.00	446.32	180.72	4.41
4	5	GST - 7.5 m	1339.6	8.21	2205.48	50.61	19.05	2011.05	1080.66	540.97	298.05	176.48	5.45
5	2	GST - 7.5 m	992.5	7.65	1885.52	50.71	20.78	1870.27	954.58	478.63	395.23	184.11	2.64
1	5	GST - 15.0 m	1026.4	7.11	1546.58	40.57	15.50	1468.06	972.59	402.21	271.16	115.70	2.52
2	1	GST - 15.0 m	709.4	6.06	1047.92	39.64	18.85	1166.41	756.46	430.36	336.84	132.56	1.15
3	6	GST - 15.0 m	1256.6	6.88	1402.08	45.13	16.14	1387.62	882.54	500.75	354.35	149.87	3.38
4	7	GST - 15.0 m	913.2	6.31	1260.96	41.71	21.12	1488.17	828.51	464.55	376.61	149.34	0.73
5	6	GST - 15.0 m	720.8	6.39	847.92	42.33	18.46	1186.52	792.48	490.70	393.02	130.00	2.41
1	3	Tank Runoff Mixture	1886.8	9.40	9822.22	67.07	30.35	4605.29	1891.15	573.15	344.46	181.91	4.71
2	8	Tank Runoff Mixture	1886.8	9.57	10960.96	70.90	26.01	5771.70	1999.22	587.23	442.58	244.48	5.26
3	4	Tank Runoff Mixture	1886.8	9.43	9127.27	68.00	28.47	3539.44	1602.98	599.29	ND	ND	ND
4	5	Tank Runoff Mixture	1886.8	9.33	9750.00	65.72	30.60	3499.22	1476.90	593.26	516.63	282.12	6.73
5	5	Tank Runoff Mixture	1886.8	9.33	10434.27	67.07	24.72	4725.96	1855.13	593.26	438.67	176.14	7.41
1	3	Rainfall	§	BD	45.63	7.03	5.28	229.26	234.14	225.24	ND	ND	ND
2	8	Rainfall	§	BD	32.37	6.80	5.23	247.36	248.55	247.36	2.00	BD	BD
3	4	Rainfall	§	BD	50.26	6.74	4.39	247.36	189.12	239.31	2.00	BD	BD
4	5	Rainfall	§	BD	46.94	6.85	5.23	255.40	264.76	235.29	0.90	BD	BD
5	5	Rainfall	§	BD	38.96	7.66	5.28	253.39	219.73	245.35	1.00	BD	BD

† ND = no data collected; BD = below detection limit of method
‡ G2 = grass (2 yr); GST = grass/shrub/tree (2 yr); G25 = grass (25+ yr); CS = contour-sorghum;
Tank Runoff Mixture = solution in mixing tanks applied to the uphill end of plots as simulated runoff;
Rainfall = well water used to simulate rainfall on the plots
§ 2.54 cm was applied to plots; actual volume applied was 566 L on 7.5 m plots and 1132 L on 15.0 m plots